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FIELD STUDY ON OCCUPANCY SCHEDULING AS A LIGHTING MANAGEMENT STRATEGY

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Abstract

Experimental results from a major demonstration of an advanced lighting energy management system at the World Trade Center are presented. The energy-saving benefits of automatically scheduling the operation of the lighting system to conform to occupancy patterns are examined. The energy saved by scheduling was measured by comparing lighting energy consumption without scheduling to consumption with scheduling. The benefits of a variety of switching scheduling are compared and the relationship between energy savings and sector size discussed. Using a loose automatic schedule with 1000 ft^2 zones, lighting energy consumption was reduced by 30% relative to baseline consumption. With a tighter schedule, energy consumption was reduced 36-37%. Based on a simple economic analysis, scheduling is shown to be a cost-effective strategy for reducing energy consumption in buildings.

Field Study on Occupancy Scheduling As a Lighting Management Strategy

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INTRODUCTION

As energy costs have risen, lighting designers and facilities managers have experienced increasing pressure to reduce the amount of energy consumed by lighting systems. Some of the most important methods for reducing this energy use fall under the category of improved lighting management practices. The elimination or reduction of lighting use when a building is unoccupied or occupied by only a few individuals--a lighting management strategy we term occupancy scheduling--can substantially reduce electrical energy use especially in buildings where manual light switches are not provided or are inaccessible to occupants. Although the simple installation or relocation of manual light switches can reduce electrical energy use in some cases [1-4], automatic switching techniques implemented with microprocessor-based systems are probably more energy-conservative in large commercial buildings because automatic switching does not rely on the goodwill and energy-consciousness of building occupants. Despite the energy-conserving potential of sophisticated lighting energy management systems and their proliferation in recent years [5], few studies have been reported in the literature to document the energy-saving benefits of the automatic scheduling strategy.

In 1978, the Lighting Systems Research Group of the Lawrence Berkeley Laboratory, under contract to the U.S. Department of Energy, initiated a Switching and Controls program to assess the energy-saving benefits of various lighting control strategies and techniques. Two demonstration projects were undertaken in order to measure the energy-saving potential of the scheduling and daylighting control strategies in functioning commercial office buildings using modern energy management systems. The 58th floor of the World Trade Center building in New York City was retrofit with a programmable switching system. The 30th floor of the Pacific Gas & Electric Company building in San Francisco was selected as the site for installation of a centralized dimming system. In a previous paper, we reported that automatic scheduling at the P.G.&E. building reduced weekday lighting energy use by 10% relative to manual operation using circuit breakers [6]. In the present paper, we describe the demonstration project at the World Trade Center and present the detailed results from the scheduling experiments conducted there.

SITE DESCRIPTION

The 58th floor of the Port Authority's One World Trade Center building was selected as the site for this study of automatic switching because it is representative of modern open-office landscaped spaces. In addition, the Port Authority Engineering Staff had already implemented the usual lighting load-reduction techniques and wanted the opportunity to test different lighting energy management strategies in their building.

Physical Site Description

The 58th floor of the World Trade Center is located approximately halfway up the north tower of the World Trade Center complex. The 58th floor occupies a 40,000-ft^2 area, but only the outer 29,000 ft^2 is usable office space. The remaining 11,000 ft^2 is core space where airshafts, elevators, and connecting corridors are located. The demonstration program was restricted to the usable area.

Ninety-six percent of the office space is open-office landscaped. Five-foot-high partitions break up the work space and between adjacent work areas. The remaining 4% of the usable floorspace consists of a conference room (790 ft^2) and two small libraries. These latter areas are each enclosed by ceiling-high partitions. Approximately one-third of the usable 29,000 ft^2 is comprised of individual work stations, each of which occupies 150 ft^2. The majority of the workers on this floor are located in these work stations. The remaining space is used for larger work spaces, reception areas, general-purpose areas, and circulation areas.

Occupant Activities

At the time this study was conducted, the 58th floor of the World Trade Center housed part of the Port Authority's Engineering Staff. The staff consisted of draftsmen, engineers, architects, administrators, and clerical support personnel. Occupants were on flexible time, typically arriving between 8:00 and 8:30 am and leaving between 4:00 and 4:30 pm. A few workers arrived at 6:30 am and some also worked until about 6:00 pm. In addition, some workers would leave the office in the middle of the day for outside assignments.

Lighting System and Visual Tasks

The lighting system on this floor consists of 450 six-lamp recessed fluorescent luminaires fitted with prismatic diffusers. These fixtures measure eight feet by 18 inches and are typically spaced on ten-foot centers in the longitudinal direction and on seven-foot centers in the lateral direction. Each fixture contains three two-lamp ballasts: one ballast controls both the inboard tubes while the remaining two ballasts each control the outboard tubes at each end of the luminaire.

The multi-ballasted luminaires are wired to the branch circuits in large blocks and are not split-wired for multi-level light control. The branch circuits for each quadrant of a floor are grouped together and are quadrant-switched at the electrical closet with large contactors.

Because this floor of the World Trade Center was originally intended for drafting tasks that require high light levels (typically 1500 lux), the power density of the original lighting system was approximately 4.4 watts/per square foot (W/ft^2). Following the oil embargo of 1973, the Engineering Staff instituted a number of energy-conserving measures including relamping the lighting system with 35-watt lamps and delamping over areas requiring less illumination (circulation and reception areas). These measures reduced the lighting power density at the time of this study to 2.6 W/ft^2.

The type of visual tasks performed at this site varied considerably: the least visually demanding tasks consisted of light reading and filing, while the most visually demanding task was drafting work. Light levels on task surfaces measured at the time of this study ranged from 750 to 1400 lux depending on the location in the building space. Some of the draftsmen supplemented the overhead lighting with individual task lights but most occupants used only the overhead lights.

Lighting System Operation Prior to Study

Before installation of the lighting energy management system used for this study, the lighting system on the 58^{th} floor was controlled, as were all the floors of the tower, by the World Trade Center's computerized switching system. This switching system was not individually wired to the contactors on each floor; therefore individual quadrants could not be switched separately. The system turned all the lights in the building on at 7:00 am and turned all the lights off at 1:00 am the following morning. There were two reasons for this 18-hour lighting schedule: first, the union contract in force at the time prohibited scheduling the activities of the cleaning crews, and second, with the existing switching system, it was not possible to provide lighting only during the time when the cleaning crews were actually present on the floor. The lighting schedule described above constituted the baseline for our analysis; the energy savings associated with automatically scheduling the operation of the lighting systems was calculated relative to this baseline.

DEMONSTRATION DESIGN

The major objective of the demonstration project at the World Trade Center was to measure, in an actual office environment, the energy-conserving potential of occupancy scheduling--the practice of automatically switching lights on and off according to predominant occupancy patterns.

<u>Operation and Installation of the Lighting Control Hardware</u>

Measurement of the energy savings associated with occupancy scheduling required installing a modern energy management system on this floor. One of the program requirements specified that the system selected for use in this project be commercially available. At the time this project started, there were relatively few lighting management systems available. The selected system consists of three major elements:

1. A microprocessor and keyboard console that are used to program and control the operation of the lighting system.
2. Remotely-located transceivers that communicate with the centrally-located microprocessor by means of a low-voltage data link.
3. Load-connected low-voltage relays that switch appropriate lighting circuits on and off.

Although the specific system components described above are unique to this product, the system is functionally similar to other programmable switching systems now on the market. Installation of this type of system in a new construction project requires that lighting fixtures be logically grouped together into independently-controllable zones (sectors). If the lighting system is composed of multi-ballasted luminaires, then the central (inboard) lamps in a fixture would typically be wired to different branch circuits than the outer (outboard) lamps. By split-wiring the fixtures in each sector to two branch circuits, each sector in the ceiling lighting system can be independently controlled to several light levels (patterns). For four-lamp luminaires, each sector can be set to any of three light levels (0, 1/2, and full on) by appropriately switching the two branch circuits feeding the sector. With three or six-lamp luminaires, each sector can be switched to any of four patterns (0, 1/3, 2/3, or full on).

The programmable system used in this study employs low-voltage relays that are wired in series to each lighting load. Each relay is independently activated (via the local transceiver) by the central microprocessor, which can be programmed to switch any group of relays on or off according to a desired schedule. Relays controlling groups of lights can also be manually activated by means of a telephone/computer interface system. Individuals needing to work during times when the lighting is programmed to be off can restore the lights in their sector by touching in a simple sequence of numbers on a telephone touch-pad.

Prior to installation of the programmable switching system, the Energy Conservation Group of the Port Authority Engineering Staff produced diagrams that assigned relay and transceiver designations to each of the 1350 ceiling fixture ballasts. By connecting one relay to each ballast in the ceiling lighting system it was possible, in this installation, to control each individual fixture to one of four light levels (0, 1/3, 2/3, and full on). Although this degree of control would rarely be economical in commercial applications, for this purpose of the study such fine control was required because it was necessary to be able change the size of individually-controlled sectors in order to examine the effects of switching zone size on energy savings. Once the engineering drawings were completed, all the ceiling fixtures were rewired and the transceivers, relays, and control unit were installed. In addition, all the fixtures were relamped with 35-watt lamps and the fixtures cleaned.

Experimental Design

A series of experiments was undertaken to measure the energy-saving potential of a variety of scheduling techniques. Each test was designed to isolate and measure the impact of the following control variables:

1. Lighting schedule tightness.
2. Fully automatic on/off versus manual on/automatic off control.
3. Trade-offs between large and small zone control.
4. Impacts of manual overrides.

Baseline. Initially, two tests were conducted to document the baseline operation of the lighting system. For the first test, the programmable switching turned all the lights on at 7:00 am and off at 1:00 am the following morning to simulated the lighting use pattern in effect on this floor before 1973. A second test simulate the lighting load profile in effect after the delamping and relamping measures described earlier.

To isolate the effects of varying schedule tightness and fully automatic versus automatic off-only control, three tests were designed, designated the loose, tight, and manual on/automatic off schedules. For all three tests, the size of the controlled sectors was held constant. The lighting system was broken down into 25 individually-controlled sectors, each about 1000 ft^2 in area. This arrangement of sectors was selected to mimic a pragmatic installation of this type of system in a new construction project in which each 1000-ft^2 sector would be controllable to four light levels using two relays per sector as previously described. Except for one sector used to control the conference room lights, all the sectors were of uniform shape and were intentionally not located to take advantage of any foreknowledge of occupant activity or location. By arranging the sectors in this manner we intended to simulate the realistic situation in which the locations of visual tasks in a new building space are not known at the time of the design process.

Loose Schedule. This test was designed to reduce lighting energy use primarily by reducing light levels after 5:30 pm to one-third for the cleaning crew. It was designated the loose schedule because lighting was switched on well before most occupants arrived and was not reduced to low level until after most occupants had left. The following weekday switching schedule was employed in this test:

- 6:30 am - Low-level "stumble lighting" (one fixture switched on per sector) to provide ingress lighting.
- 7:30 am - All sectors to full lighting pattern.
- 5:30 pm - All sectors to one-third lighting. pattern.
- 11:00 pm - All sectors off except stumble lights.
- 1:00 am - All lights off.

Individuals needing to work before 7:30 am or after 5:30 pm could obtain full lighting in their sector using the telephone override system. On weekends, lighting was not automatically provided but individual sectors could be switched on with the overrides.

Tight Schedule. This test was designed to reduce energy use further by placing the automatic switching times closer to the time at which occupants arrived or departed and by reducing light levels to one-third level during most of the lunch hour:

- 6:30 am - Stumble lights on.
- 7:30 am - All sectors to one-third level.
- 7:45 am - All sectors to full lighting pattern.
- 12:15 pm - All sectors to one-third level.
- 1:00 pm - All sectors to full lighting pattern.
- 4:45 pm - All sectors to one-third level.
- 11:00 pm - All lights off except stumble lights.
- 1:00 am - All lights off.

As before, individuals needing to work during periods of reduced light levels could obtain full lighting using the overrides. For this test, manual overrides would be more important because it was expected that some individuals would need them to restore their lights to full level during lunch. On weekends, no lighting was provided but could be manually activated if necessary.

Manual on/automatic off schedule: With this test the control system was used only to switch lights off or to low level. Except for stumble lighting at the beginning of the day, no other lighting was automatically provided. The first individual to arrive in each sector would switch on the lights manually with the overrides.

- 6:30 am - Stumble lights on.
- 12:15 pm - All sectors to one-third level.
- 4:45 pm - All sectors to one-third level.
- 11:00 pm - All lights off except stumble lights.
- 1:00 am - All lights off.

Overrides would clearly prove important in this test because they are the only means by which occupants can obtain lighting in their sectors in the morning and after the lunch hour. As in the previous tests, no lighting was automatically provided on weekends. With the exception of the manual on feature, this test was identical to the automatic tight schedule so that any potential benefits associated with manual on control could be identified by comparing test results.

The above tests all used the same 1000 ft^2 sectors to permit meaningful intercomparisons. To examine the impact of decreased sector size on energy savings, a final test was designed with the lighting system broken down into very small sectors.

<u>Manual on/automatic off schedule with very small sectors</u>: By exploiting the full resolution of the control system installed at this site, this test was designed to measure the energy savings when scheduling was implemented with ultimate fine control. In this test, the lights for each of the 100 work stations was to be independently controllable to four light levels. Independent sectors were also provided for all larger work areas and one long, winding sector was defined for the circulation area that connected the various work stations. Since independent fixture control was to be used, it was also possible to tune the lighting system further by simply not turning on more than 100 fixtures that were located above under-utilized areas.

- 6:30 am - Stumble lights on.
- 8:00 am - Circulation sector on to one-sixth level.
- 12:15 pm - Any manually activated sectors to one-third level.
- 5:00 pm - All lighting sectors to one-sixth level.
- 10:00 pm - All lights off except stumble lights.
- 11:00 pm - All lights off.

Workers arriving in their individual workstations at the beginning of the day turned on their own lights using the overrides. Workers returning from lunch could restore their lights to full level if they so desired.

Each of the six tests described in this section were one to two weeks in duration. The tests were spread over an eight-month period and were interspersed with other tests designed to isolate the impact of daylight-linked lighting load reductions. Prior to each test, bulletins were distributed to occupants informing them in general terms of the nature of the test and reminding them to use the telephone overrides if necessary.

Monitoring Instrumentation

Energy use for lighting was measured using the output record of the installed energy management system. Every time the lighting system changed state, either by a pre-programmed schedule or by a manual override, the system recorded which sector (or sectors) were changed and to what level. From this information, the electrical power to all the lighting on the floor or any subset of lights could be calculated. To facilitate processing and reduction of the experimental data, all lighting activities were recorded onto a magnetic data cartridge system as well as onto a hard-copy printer. Following each test event, the magnetic tape cartridges were shipped to LBL and the data transferred to the LBL CDC 7600 and VAX 11/780 computers for analysis. A computer program was developed by one of the authors (Karayel) to translate the record of sector switching activity to a running record of lighting power demand.

During the analysis of the experimental data, it was found that the sector for the conference room lights was being switched on and off at unpredictable times, making meaningful comparisons between similar test results difficult. As a result, we eliminated the switching activity of the conference room from our data in the reduction process.

RESULTS

The results for each experimental event relating to the use of occupancy scheduling are shown as plots of number of ballasts (relays) turned on versus time of day for each day of the test. As each ballast was known to use 85 watts, the number of ballasts on is directly proportional to the instantaneous lighting load. In our analysis, we have treated only weekday data because this floor of the World Trade Center is rarely used during the weekend and the results are therefore not meaningful.

Baseline Before and After DeLamping

Figure 1 shows the lighting load profile for both the original lighting system and after delamping and relamping with 35-watt lamps. The lighting demand for the original lighting system was 122 kW (1271 ballasts x 96 watts/ballast) with average daily usage of 2196 kWh for the entire floor (excluding the conference room). Post-embargo lighting demand was reduced to 93 kW, (1096 ballasts x 85 watts/ballast) with daily energy usage of 1677 kWh. Of this total reduction in demand (29 kW), 17 kW is attributable to the removal of 40-lamps over areas requiring less illumination. The remaining 12 kW reduction was due to replacing the remaining 40-watt fluorescent lamps with 35-watt lamps. For our analysis of the energy savings associated with scheduled lighting operation, we used the lower power profile as the baseline because this was the lighting power profile in effect immediately prior to this study.

Automatic Loose Schedule with 1000-ft^2 Sectors

Figure 2 shows the lighting power profile for each weekday for the test in which the lights were automatically switched on at 7:30 am and switched to one-third level for the evening cleaning tasks. The lighting usage attributable to occupants arriving before the automatically scheduled on-time at 7:30 am is evident in the figure. Between 5:30 pm and 8:30 pm, the measured lighting demand is somewhat higher than the programmed one-third level due to occupants using the overrides after 5:30 pm. Note that the lighting demand drops to approximately one-third of full level at 8:30 pm because the control system was programmed to switch all overridden sectors to one-third at this time. This technique of switching overridden sectors to low level at a pre-programmed time was adopted to prevent the lights in manually overridden sectors from remaining at full level throughout the evening. It is also evident from the figure that the lighting power profiles for different test days are quite similar despite the slight differences in override use patterns.

Using the automatically-activated loose schedule, lighting energy use was reduced from 1677 kWh/weekday to an average of 1178 kWh/weekday, a 30% reduction in daily lighting energy consumption.

Automatic Tight Schedule With 1000 ft^2 Sectors

Figure 3 shows the lighting demand measured for weekdays during the second scheduling test. Full lighting was activated 15 minutes later (7:45 am) than in the previous test and light levels reduced to one-third level at 4:45 pm. Lighting demand between 12:15 pm and 1:00 pm was significantly reduced due to the automatically programmed lunch-time set-back. The lighting demand does not drop all the way to one-third, however, due to the use of overrides by individuals working through lunchtime. Average lighting energy consumption for this test was 1077 kWh/weekday: a reduction of 36% relative to the baseline operation (delamped) and a 9% reduction relative to the automatic loose schedule described previously.

Manual On/Automatic Off Schedule with 1000-ft^2 Sectors

Further slight reductions in lighting power and energy use occurred when the first arrivals in each sector manually engage the lighting rather than having it provided automatically at a preprogrammed time. Lighting was automatically reduced to one-third level at 12:15 pm and at 4:45 pm as in the previous test. Because lighting in each 1000-ft^2 sector was not activated until the first individual to arrive switched the sector lights on, lighting demand in the early morning and afternoon was generally lower in these tests (Fig. 4) than in either of the fully automatic schedule tests described previously. Note that lighting demand did not reach baseline levels until approximately 9:30 am. Following the lunch time set-back, lighting demand consistently fell short of the baseline level.

For these manual on/automatic off test days, lighting energy use averaged 1052 kWh/weekday, a reduction of 37% relative to the baseline case and a 11% reduction relative to the automatic loose scheduling test described earlier. Relative to the automatic tight schedule, manual on/automatic off control reduced average daily energy use by only 2% which is of questionable statistical significance.

Manual On/Automatic Off Schedule with Very Small Sectors

Figure 5 shows the lighting power profiles for the manual on/automatic off schedule using workstation-sized sectors. It is evident from the graph that the utilization of very small sectors drastically reduced lighting demand throughout the day, especially in the afternoons. The automatic provision of stumble lighting is seen at 6:30 am for each day. Between 6:30 am and 8:00 am, there is a gradual increase in lighting demand as individuals arriving turned on the lights in their individual work areas. Since the vast majority of occupants arrive between 8:00 and 8:30 am, there is a rapid increase in demand during this time as these occupants engage their lights. Although the major influx of people entering the building space ends at 8:30 am, people still continue to arrive until about 11:00 am. The maximum lighting demand in the morning never exceeded 73% of the baseline lighting load. Following the lunchtime set-back at 12:15 pm, a number of individuals immediately restored their lights to full level, presumably because they intended to work through lunch. Between 1:00 pm and 1:30 pm there is a rapid increase in lighting demand as expected; however, maximum lighting demand in the afternoon never exceeded 56% of the baseline demand. At 5:00 pm the lighting system is forced to the one-sixth level, and the few individuals working after this overrode their lights. All lighting was shut off at 11:00 pm. As the sectors in this experiment were very small (mean size 160 ft^2), any overrides after the evening reduction at 5:00 pm have only minor impact on the lighting demand.

Average lighting energy use for this test was only 604 kWh/weekday, a reduction of 64% relative to the baseline case and a 49% reduction beyond the automatic loose schedule test with 1000-ft^2 sectors.

Result Summary

Table 1 summarizes the results of all the tests. The table is presented in matrix form to permit comparisons of the energy savings between the various tests.

TABLE 1

REDUCTION IN DAILY LIGHTING ENERGY USE AND PERCENT CHANGE FROM ↓

RELATIVE TO ↓	MANUAL ON/ AUTOMATIC OFF (WORKSTATION CONTROL)	MANUAL ON/ AUTOMATIC OFF (1000-ft^2 SECTORS)	TIGHT SCHEDULE (1000-ft^2 SECTORS)	LOOSE SCHEDULE (1000-ft^2 SECTORS)
BASELINE	1073 kWh 64%	625 kWh 37%	600 kWh 36%	499 kWh 30%
LOOSE SCHEDULE w/1000-ft^2 SECTORS	574 kWh 49%	126 kWh 11%	101 kWh 9%	-----
TIGHT SCHEDULE w/1000-ft^2 SECTORS	473 kWh 44%	25 kWh 2%	-----	-----
MANUAL ON/AUTOMATIC OFF SCHEDULE w/1000-ft^2 SECTORS	448 kWh 43%	-----	-----	-----

To find the relative decrease in lighting energy use of, for example, the tight schedule relative to the loose schedule, one would select the row labeled loose and the column labeled tight to find that the daily lighting energy use reduction was 101 kWh, a decrease of 9%.

DISCUSSION

It is evident from the data presented here that scheduling the operation of the lighting system to conform more closely to occupancy needs and flow patterns can conserve a considerable amount of energy. In this building, as in many commercial buildings, the vast majority of occupants are present only during the core time, that is, between 8:00

am and 5:00 pm. With the exception of a few early arriving and late departing individuals, the only function of the lighting system outside the core hours is to provide light for the cleaning crew, whose tasks are not visually demanding. The 30% reduction in lighting energy use measured using the automatic loose schedule was almost entirely attributable to reducing light levels to one-third during non-core times.

By using the tight schedule, to switch the lights on slightly later in the morning and slightly earlier in the evening, we were able to reduce energy use an additional 9% relative to the loose schedule. Part of this savings was a consequence of the lunchtime setback, which significantly impacted lighting demand during the lunch hour. The placement of the setback time at 12:15 pm rather than at noon is important because a premature level shift would probably cause the occupants to restore their sectors to full lighting even if they intended to depart momentarily for lunch. For similar reasons, we did not attempt a level reduction earlier than 4:45 pm with this test.

By allowing occupants to switch on their lights in the morning and after lunch, a further reduction in energy use was measured. Although the lighting load takes longer to reach the baseline level using the manual on/automatic off schedule than in previous tests, all sectors are eventually activated in the morning because several occupants share each 1000-ft^2 sectors, and therefore the probability is high that at least one individual will arrive and switch on the lights. It is interesting to note, however, that after the automatic lunchtime setback, a few sectors are consistently left at one-third level and were not restored to full lighting level by the occupants returning from lunch. One explanation for this behavior is that the one-third electric light level plus the availability of daylight was sufficient to obviate the need for full lighting during the afternoon. An alternative explanation is that some sectors were simply not occupied after the lunch hour due to occupants being offsite.

A comparison of the data from the tight and manual on/automatic off tests revealed only an insignificant difference in overall lighting energy consumption. This indicates that with 1000-ft^2 sectors there is little energy-saving benefit to be gained by having the workers turn on their own lights rather than providing light automatically at a preprogrammed time. There was some indication that manual on/automatic off control can reduce lighting demand during the afternoon hours, however.

The workstation control data showed a large reduction not only in overall energy use but also in lighting demand throughout the core hours. This result was in sharp contrast to the previous tests using 1000 ft^2 sectors in which lighting demand during the core hours was at best only slightly reduced. The cause of the lighting demand reduction with workstation control is due to several factors. First, the employment of extremely fine control resolution in this test permitted the elimination of about 100 ballasts located over under-utilized areas. Second, although lighting sectors were defined for all workstations, detailed analysis of the data revealed that 20% of the workstation sectors were never turned on during the entire test, presumably due to under-utilization of these areas. Third, even in those workstations that were usually occupied, absenteeism and vacancies accounted for some of the lighting load reduction. Finally, the even larger reductions in lighting load in the afternoon hours suggests that the availability of daylight in conjunction with the one-third electric lighting level may have been sufficient for some occupants' needs. The latter interpretation of the data is consistent with that of Crisp [3], who found that the probability of occupants turning on their area lights after lunch was lower than 50% given daylight factors as low as 0.5% (typically 5 footcandles). Regardless of the interpretation, however, it is evident that the combination of very small sectors with manual on/automatic off control allows a considerable reduction in lighting demand throughout the core hours. Of course, the potential benefits of these reductions must be weighed against the formidable cost of providing this degree of control.

Use of Overrides

The importance of overrides was demonstrated repeatedly throughout this study. If the probability distribution of people arriving and departing as a function of time was sharply peaked at known times and had no "tail", then overrides would not prove necessary because the lights could simply be switched on immediately prior to occupancy and switched off immediately after vacancy. This is rarely the case, however, since at least a few individuals will usually work outside regular core times. If overrides were not provided, it would be necessary to use a long lighting schedule to accommodate these individuals, significantly reducing any possible energy savings. By providing accessible override switches for local lighting sectors, a relatively tight schedule can be employed to provide lighting for the majority of people while the overrides are used to meet the lighting needs of those individuals who work outside the scheduled on-times.

For the manual on/automatic off lighting schedules, overrides also served another useful function. Because the overrides must be used by the occupants to obtain light in their local areas, it is possible to capture some additional energy savings as a result of zone vacancies due to absenteeism, under-utilization of building space, and the availability of daylight. As our data indicate, the amount of energy that can be conserved under these conditions is directly related to the size of the switched sectors. On the other hand, the cost of the installed controls for this type of system increases in proportion to the number of independently-controllable sectors. This implies that there is an optimum sector size that can be determined for a particular energy cost and lighting power density if the occupancy distribution is known. More work needs to be done in this area, however, before it is possible to develop any generalized lighting control design procedures.

Economic Analysis For 1000 ft^2 Sector Control

Based on the energy savings measured in this study, one can estimate the cost-effectiveness of automatic controls for scheduling for a large new construction project in which the lighting system is split-wired for multi-level control and controls are installed as part of the design process. Projecting the energy savings previously described to 260 working days per year, the loose scheduling technique would reduce annual lighting costs by $7850 per floor relative to basecase costs assuming an energy cost of $0.06/kWh. Since the installed cost of the controls (relays, wiring, etc.) in a new construction situation is approximately $100 per control point (relay), the initial investment for the controls would be $5000/floor (25 sectors/floor x 2 relays/sector x $100/relay). From this one can calculate that the simple payback period (initial investment costs ÷ annual energy cost savings) for the loose scheduling technique is less than 8 months. Similarly, for the tight and manual on/automatic off schedules, the annual energy cost savings would be $9420 and $9680, respectively, yielding paybacks of between 6 and 7 months.

The brevity of the simple paybacks estimated above is of course due partly to the long baseline lighting schedule in effect prior to this study. To show that these scheduling techniques are still economical in buildings with shorter baseline hours, we recalculated the energy savings assuming a building in which the original lighting hours are 7:00 am to 9:00 pm. Because the baseline lighting hours are, in this case, only 14 hours a day instead of 18 hours, the energy savings for the loose, tight, and manual on/automatic off schedules relative to the modified baseline are reduced to 16%, 24% and 26%, respectively. Despite these reduced energy savings, annual energy cost savings are projected to be $3260, $4880, and $5290 per floor with associated simple payback periods of 18, 12, and 11 months for the loose, tight, and manual on/automatic off schedules, respectively. Since paybacks of less than two years are generally considered acceptable for this kind of investment in new construction [5], it is clear that the investment in control hardware to automatically schedule the operation of the lighting system can be economically justified.

Economic Analysis For Workstation Control

Although the measured energy savings with the workstation-sized sectors was very large (64% relative to the baseline at World Trade Center and 57% relative to a building using the modified 14-hour baseline), this degree of control can only be economically justified if energy costs are very high. Workstation control requires the installation of two relays per fixture; the cost of installation would therefore be about $90,000/floor in a new construction situation. At $0.06/kWh, the projected energy cost savings are $16,740/floor/year relative to the World Trade Center's 18-hour baseline and $11,600/floor/year relative to the 14-hour baseline. Since this equates to payback periods of 5.4 and 7.8 years respectively, installation of this degree of control is not economical. At $0.14/kWh (current electrical energy costs in New York City), the paybacks would be 2.3 and 3.3 years.

Interaction With Heating and Cooling Loads

In our analysis, we have not considered the impact of reduced lighting energy consumption on heating and cooling loads. It is clear that one consequence of automatically scheduled lighting is decreased cooling loads and increased heating loads. Although there are undoubtedly some buildings in cold climates where the increase in heating loads would reduce the net savings from scheduled lighting, it is also true that in most large buildings cooling loads dominate. In the latter cases, any reduction in lighting energy consumption only adds to energy savings due to the accompanying reduction in cooling loads.

CONCLUSION

It is evident from this study that automatically scheduling the operation of the lighting system to closely conform to occupancy patterns substantially reduced energy consumption for lighting. Using a simple loose schedule technique with 1000-ft^2 sectors, a 30% reduction in lighting energy use was measured relative to baseline operation. By employing a tighter automatic schedule, lighting energy use was reduced 36% relative to baseline operation with similar results for a manual on/automatic off switching technique. With work station-sized sectors, lighting energy use was reduced 64% relative to baseline operation, clearly demonstrating the relationship between energy savings and sector size. Using a simple economic analysis, we have shown that automatic scheduling with 1000-ft^2 sectors is a cost-effective method to reduce lighting energy consumption in buildings.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the able assistance of Daniel Goldberg, Harry Ryan, Herman Turk, Dennis Avenoso and Helen Matthews of the Port Authority's Engineering Staff without whose efforts this project would have been most difficult. We also acknowledge the technical assistance of David Peterson.

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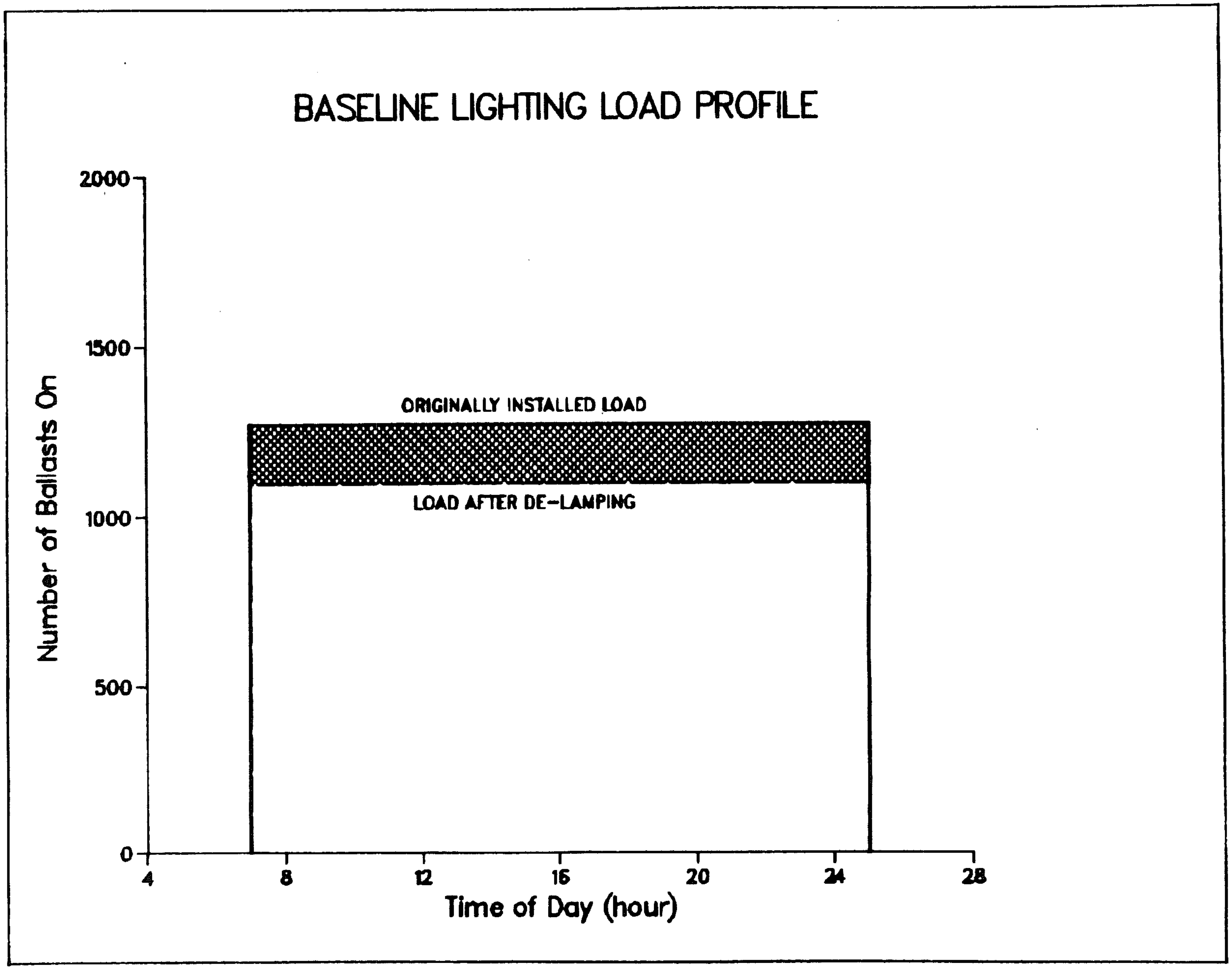


BASELINE LIGHTING LOAD PROFILE
Number of Ballasts On
2000
1500
1000
500
0
ORIGINALLY INSTALLED LOAD
LOAD AFTER DE-LAMPING
4
8
12
16
20
24
28
Time of Day (hour)

FIGURE 1

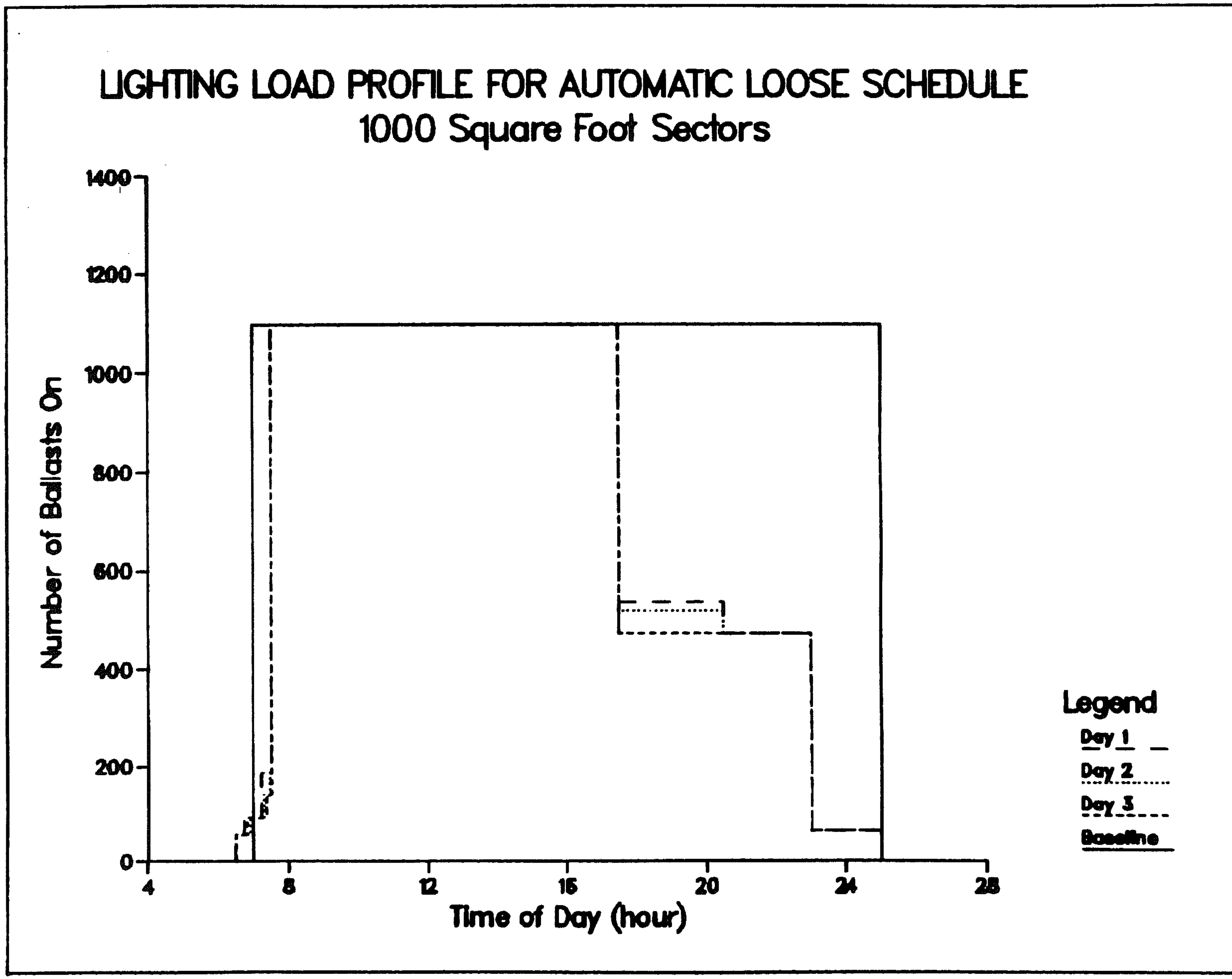
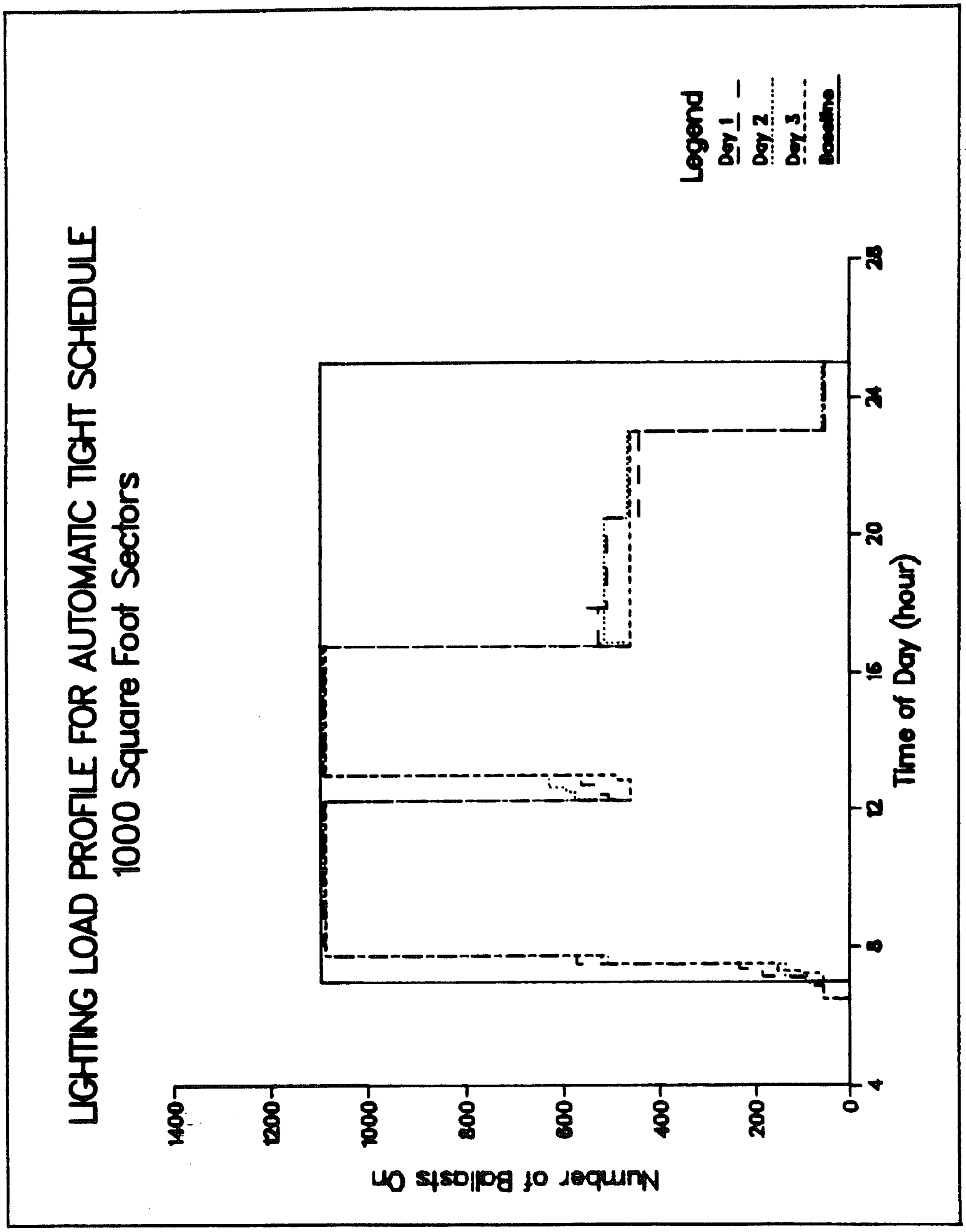

LIGHTING LOAD PROFILE FOR AUTOMATIC LOOSE SCHEDULE
1000 Square Foot Sectors
Number of Ballasts On
0
200
400
600
800
1000
1200
1400
4
8
12
16
20
24
28
Time of Day (hour)
Legend
Day 1
Day 2
Day 3
Baseline

FIGURE 2



LIGHTING LOAD PROFILE FOR AUTOMATIC TIGHT SCHEDULE
1000 Square Foot Sectors
Number of Ballasts On
0
200
400
600
800
1000
1200
1400
4
8
12
16
20
24
28
Time of Day (hour)
Legend
Day 1
Day 2
Day 3
Baseline

FIGURE 3

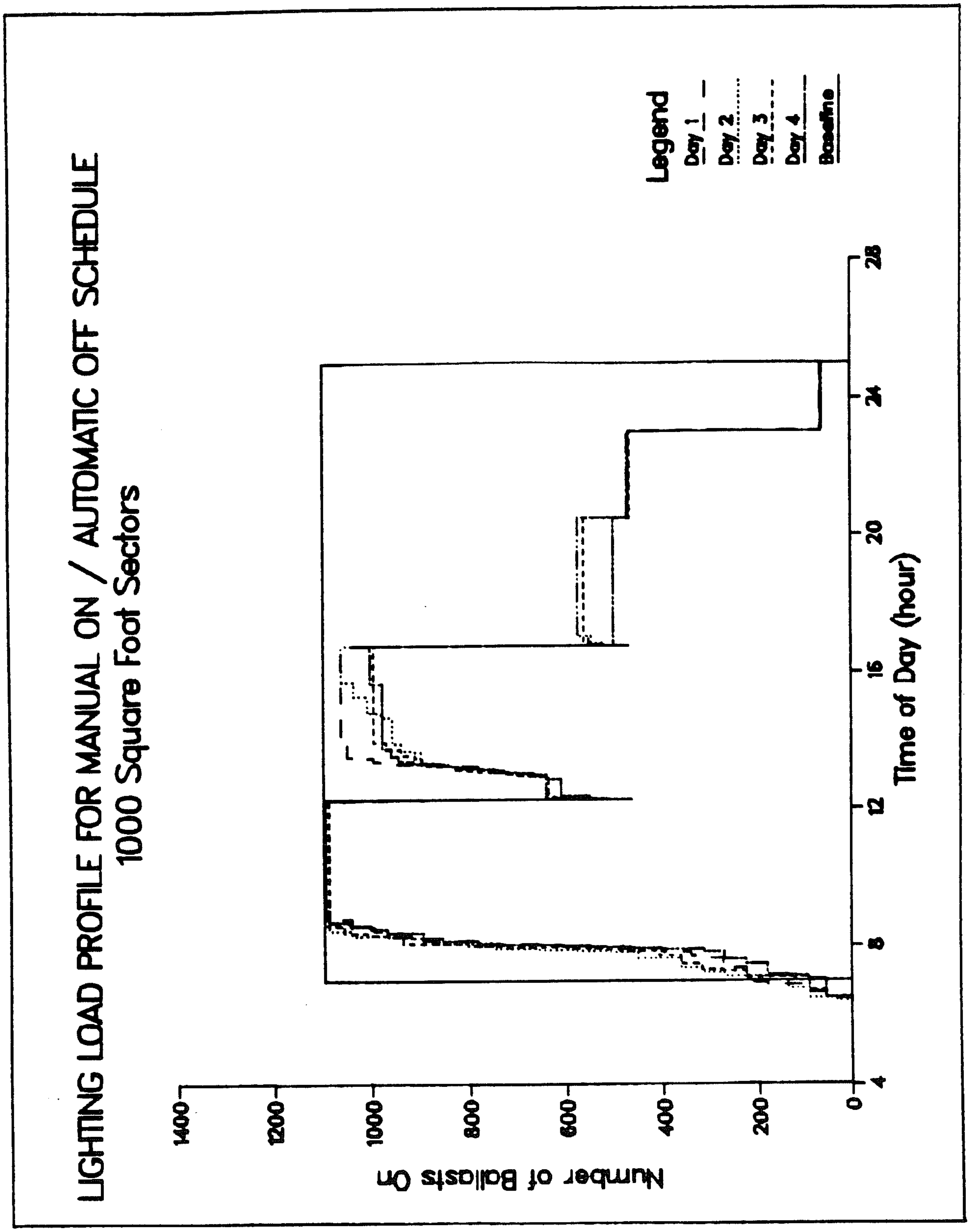

LIGHTING LOAD PROFILE FOR MANUAL ON / AUTOMATIC OFF SCHEDULE
1000 Square Foot Sectors
Number of Ballasts On
0
200
400
600
800
1000
1200
1400
Time of Day (hour)
4
8
12
16
20
24
28
Legend
Day 1
Day 2
Day 3
Day 4
Baseline

FIGURE 4

LIGHTING LOAD PROFILE FOR MANUAL ON / AUTOMATIC OFF SCHEDULE
Mean Sector Size 160 Square Feet

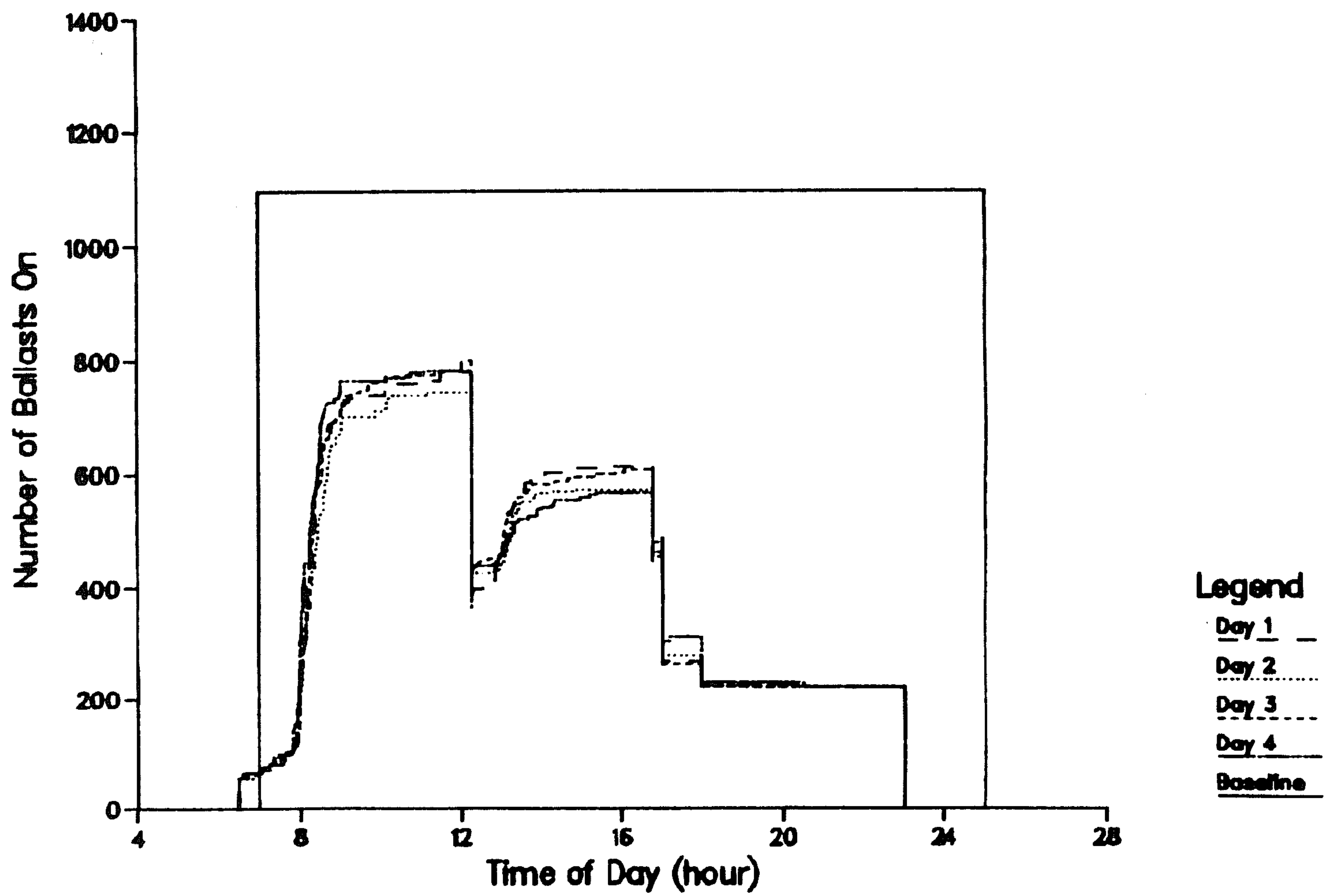


FIGURE 3

Reprinted from the May 1984 issue of Lighting Design & Application with permission of the Illuminating Engineering Society of North America.

Field study on occupancy scheduling as a lighting management strategy

F. Rubinstein, M. Karayel, and R. Verderber

Introduction

As energy costs have risen, lighting designers and facilities managers have experienced increasing pressure to reduce the amount of energy consumed by lighting systems. Some of the most important methods for reducing this energy use fall under the category of improved lighting management practices. The elimination or reduction of lighting use when a building is unoccupied or occupied by only a few individuals—a lighting management strategy we term *occupancy scheduling*—can substantially reduce electrical energy use especially in buildings where manual light switches are not provided or are inaccessible to occupants. Although the simple installation or relocation of manual light switches can reduce electrical energy use in some cases,[1-4] automatic switching techniques implemented with microprocessor-based systems are probably more energy-conservative in large commercial buildings because automatic switching does not rely on the goodwill and energy-consciousness of building occupants. Despite the energy-conserving potential of sophisticated lighting energy management systems and their proliferation in recent years,[5] few studies have been reported in the literature to document the energy-saving benefits of the automatic scheduling strategy.

In 1978, the Lighting Systems Research Group of the Lawrence Berkeley Laboratory, under contract to the US Department of Energy, initiated a Switching and Controls program to assess the energy-saving benefits of various lighting control strategies and techniques. Two demonstration projects were undertaken in order to measure the energy-saving potential of the scheduling and daylighting control strategies in functioning commercial office buildings using modern energy management systems. The 58th floor of the World Trade Center building in New York City was retrofit with a programmable switching system. The 30th floor of the Pacific Gas & Electric Company building in San Francisco was selected as the site for installation of a centralized dimming system. In a previous paper, we reported that automatic scheduling at the P.G.&E. building reduced weekday lighting energy use by 10 percent relative to manual operation using circuit breakers.[6] In the present paper, we describe the demonstration project at the World Trade Center and present the detailed results from the scheduling experiments conducted there.

Site description

The 58th floor of the Port Authority's One World Trade Center building was selected as the site for this study of automatic switching because it is representative of modern open-office landscaped spaces. In addition, the Port Authority Engineering Staff had already implemented the usual lighting load-reduction techniques and wanted the opportunity to test different lighting energy management strategies in their building.

The authors: Lighting Systems Research, Lawrence Berkeley Laboratory, University of California, Berkeley, CA. This paper has been presented at the 1983 Annual IES Conference, held August 7–11, in Los Angeles, CA.

Physical site description

The 58th floor of the World Trade Center is located approximately halfway up the north tower of the World Trade Center complex. The 58th floor occupies a 40,000-ft^2 area, but only the outer 29,000 ft^2 is usable office space. The remaining 11,000 ft^2 is core space where airshafts, elevators, and connecting corridors are located. The demonstration program was restricted to the usable area.

Ninety-six percent of the office space is open-office landscaped. Five-foot-high partitions break up the work space and between adjacent work areas. The remaining 4 percent of the usable floorspace consists of a conference room (790 ft^2) and two small libraries. These latter areas are each enclosed by ceiling-high partitions. Approximately one-third of the usable 29,000 ft^2 is comprised of individual work stations, each of which occupies 150 ft^2. The majority of the workers on this floor are located in these work stations. The remaining space is used for larger work spaces, reception areas, general-purpose areas, and circulation areas.

Occupant activities

At the time this study was conducted, the 58th floor of the World Trade Center housed part of the Port Authority's Engineering Staff. The staff consisted of draftsmen, engineers, architects, administrators, and clerical support personnel. Occupants were on flexible time, typically arriving between 8:00 and 8:30 am and leaving between 4:00 and 4:30 pm. A few workers arrived at 6:30 am and some also worked until about 6:00 pm. In addition, some workers would leave the office in the middle of the day for outside assignments.

Lighting system and visual tasks

The lighting system on this floor consists of 450 six-lamp recessed flourescent luminaires fitted with prismatic diffusers. These fixtures measure 8 ft by 18 inches and are typically spaced on 10-ft centers in the longitudinal direction and on 7-ft centers in the lateral direction. Each fixture contains three two-lamp ballasts: one ballast controls both the inboard tubes while the remaining two ballasts each control the outboard tubes at each end of the luminaire.

The multi-ballasted luminaires are wired to the branch circuits in large blocks and are not split-wired for multi-level light control. The branch circuits for each quadrant of a floor are grouped together and are quadrant-switched at the electrical closet with large contactors.

Because this floor of the World Trade Center was originally intended for drafting tasks that require high light levels (typically 1500 lx), the power density of the original lighting system was approximately 4.4 W/ft^2. Following the oil embargo of 1973, the engineering staff instituted a number of energy-conserving measures including relamping the lighting system with 35-W lamps and delamping over areas requiring less illumination (circulation and reception areas). These measures reduced the lighting power density at the time of this study to 2.6 W/ft^2.

The type of visual tasks performed at this site varied considerably: the least visually demanding tasks consisted of light reading and filing, while the most visually demanding task was drafting work. Light levels on task surfaces measured at the time of this study ranged from 750 to 1400 lux depending on the location in the building space. Some of the draftsmen supplemented the overhead lighting with individual task lights but most occupants used only the overhead lights.

Lighting system operation prior to study

Before installation of the lighting energy management system used for this study, the lighting system on the 58th floor was controlled, as were all the floors of the tower, by the World Trade Center's computerized switching system. This switching system was not individually wired to the contactors on each floor; therefore individual quadrants could not be switched separately. The system turned all the lights in the building on at 7:00 am and turned all the lights off at 1:00 am the following morning. There were two reasons for this 18-hour lighting schedule: first, the union contract in force at the time prohibited scheduling the activities of the cleaning crews, and second, with the existing switching system, it was not possible to provide lighting only during the time when the cleaning crews were actually present on the floor. The lighting schedule described above constituted the baseline for our analysis; the energy savings associated with automatically scheduling the operation of the lighting systems was calculated relative to this baseline.

Demonstration design

The major objective of the demonstration project at the World Trade Center was to measure, in an actual office environment, the energy-conserving potential of occupancy scheduling—the practice of automatically switching lights on and off according to predominant occupancy patterns.

Operation and installation of the lighting control hardware

Measurement of the energy savings associated with occupancy scheduling required installing a modern energy management system on this floor. One of the program requirements specified that the system selected for use in this project be commercially available. At the time this project started, there were relatively few lighting management systems available. The selected system consists of three major elements:

1. A microprocessor and keyboard console that are used to program and control the operation of the lighting system.

2. Remotely-located transceivers that communicate with the centrally-located microprocessor by means of a low-voltage data link.

3. Load-connected low-voltage relays that switch appropriate lighting circuits on and off.

Although the specific system components described above are unique to this product, the system is functionally similar to other programmable switching systems now on the market. Installation of this type of system in a new construction project requires that lighting fixtures be logically grouped together into independently-controllable zones (sectors). If the lighting system is composed of multi-ballasted luminaires, then the central (inboard) lamps in a fixture would typically be wired to different branch circuits than the outer (outboard) lamps. By split-wiring the fixtures in each sector to two branch circuits, each sector in the ceiling lighting system can be independently controlled to several light levels (patterns). For four-lamp luminaires, each sector can be set to any of three light levels (0, ½, and full on) by appropriately switchng the two branch circuits feeding the sector. With three or six-lamp luminaires, each sector can be switched to any of four patterns (0, ⅓, ⅔, or full on).

The programmable system used in this study employs low-voltage relays that are wired in series to each lighting load. Each relay is independently activated (via the local transceiver) by the central microprocessor, which can be programmed to switch any group of relays on or off according to a desired schedule. Relays controlling groups of lights can also be manually activated by means of a telephone/computer interface system. Individuals needing to work during times when the lighting is programmed to be off can restore the lights in their sector by touching in a simple sequence of numbers on a telephone touch-pad.

Prior to installation of the programmable switching system, the Energy Conservation Group of the Port Authority Engineering Staff produced diagrams that assigned relay and transceiver designations to each of the 1,350 ceiling fixture ballasts. By connecting one relay to each ballast in the ceiling lighting system it was possible, in this installation, to control each individual fixture to one of four light levels (0, ⅓, ⅔, and full on). Although this degree of control would rarely be economical in commercial applications, for this purpose of the study such fine control was required because it was necessary to be able to change the size of individually-controlled sectors in order to examine the effects of switching zone size on energy savings. Once the engineering drawings were completed, all the ceiling fixtures were rewired and the transceivers, relays, and control unit were installed. In addition, all the fixtures were relamped with 35-W lamps and the fixtures cleaned.

Experimental design

A series of experiments was undertaken to measure the energy-saving potential of a variety of scheduling techniques. Each test was designed to isolate and measure the impact of the following control variables:

1. Lighting schedule tightness.

2. Fully automatic on/off versus manual on/automatic off control.

3. Trade-offs between large and small zone control.

4. Impacts of manual overrides.

Baseline. Initially, two tests were conducted to document the baseline operation of the lighting system. For the first test, the programmable switching turned all the lights on at 7:00 am and off at 1:00 am the following morning to simulate the lighting use pattern in effect on this floor before 1973. A second test simulated the lighting load profile in effect after the delamping and relamping measures described earlier.

To isolate the effects of varying schedule tightness and fully automatic versus automatic off-only control, three tests were designed, designated the loose, tight, and manual on/automatic off schedules. For all three tests, the size of the controlled sectors was held constant. The lighting system was broken down into 25 individually-controlled sectors, each about 1000 ft^2 in area. This arrangement of sectors was selected to mimic a pragmatic installation of this type of system in a new construction project in which each 1000-ft^2 sector would be controllable to four light levels using two relays per sector as previously described. Except for one sector used to control the conference room lights, all the sectors were of uniform shape and were intentionally not located to take advantage of any foreknowledge of occupant activity or location. By arranging the sectors in this manner we intended to simulate the realistic situation in which the locations of visual tasks in a new building space are not known at the time of the design process.

Loose schedule. This test was designed to reduce lighting energy use primarily by reducing light levels after 5:30 pm to one-third for the cleaning crew. It was designated the loose schedule because lighting was switched on well before most occupants arrived and was not reduced to low level until after most occupants had left. The following weekday switching schedule was employed in this test:

- 6:30 am—Low-level "stumble lighting" (one fixture switched on per sector) to provide ingress lighting.
- 7:30 am—All sectors to full lighting pattern.
- 5:30 pm—All sectors to one-third lighting pattern.
- 11:00 pm—All sectors off except stumble lights.
- 1:00 am—All lights off.

Individuals needing to work before 7:30 am or after 5:30 pm could obtain full lighting in their sector using the telephone override system. On weekends, lighting was not automatically provided but individual sectors could be switched on with the overrides.

Tight schedule. This test was designed to reduce energy use further by placing the automatic switching times closer to the time at which occupants arrived or departed and by reducing light levels to one-third level during most of the lunch hour:

- 6:30 am—Stumble lights on.
- 7:30 am—All sectors to one-third level.
- 7:45 am—All sectors to full lighting pattern.
- 12:15 pm—All sectors to one-third level.
- 1:00 pm—All sectors to full lighting pattern.
- 4:45 pm—All sectors to one-third level.
- 11:00 pm—All lights off except stumble lights.
- 1:00 am—All lights off.

As before, individuals needing to work during periods of reduced light levels could obtain full lighting using the overrides. For this test, manual overrides would be more important because it was expected that some individuals would need them to restore their lights to full level during lunch. On weekends, no lighting was provided but could be manually activated if necessary.

Manual on/automatic off schedule: With this test the control system was used only to switch lights off or to low level. Except for stumble lighting at the beginning of the day, no other lighting was automatically provided. The first individual to arrive in each sector would switch on the lights manually with the overrides.

- 6:30 am—Stumble lights on.
- 12:15 pm—All sectors to one-third level.
- 1:00 pm—All sectors to full lighting pattern.
- 4:45 pm—All sectors to one-third level.
- 11:00 pm—All lights off except stumble lights.
- 1:00 am—All lights off.

Overrides would clearly prove important in this test because they are the only means by which occupants can obtain lighting in their sectors in the morning and after the lunch hour. As in the previous tests, no lighting was automatically provided on weekends. With the exception of the manual on feature, this test was identical to the automatic tight schedule so that any potential benefits associated with manual on control could be identified by comparing test results.

The above tests all used the same 1000 ft^2 sectors to permit meaningful intercomparisons. To examine the impact of decreased sector size on energy savings, a final test was designed with the lighting system broken down into very small sectors.

Manual on/automatic off schedule with very small sectors: By exploiting the full resolution of the control system installed at this site, this test was designed to measure the energy savings when scheduling was implemented with ultimate fine control. In this test, the lights for each of the 100 work stations was to be independently controllable to four light levels. Independent sectors were also provided for all larger work areas and one long, winding sector was defined for the circulation area that connected the various work stations. Since independent fixture control was to be used, it was also possible to tune the lighting system further by simply not turning on more than 100 fixtures that were located above under-utilized areas.

- 6:30 am—Stumble lights on.
- 8:00 am—Circulation sector on to one-sixth level.
- 12:15 pm—Any manually activated sectors to one-third level.
- 5:00 pm—All lighting sectors to one-sixth level.
- 10:00 pm—All lights off except stumble lights.
- 11:00 pm—All lights off.

Workers arriving in their individual workstations at the beginning of the day turned on their own lights using the overrides. Workers returning from lunch could restore their lights to full level if they so desired.

Each of the six tests described in this section were one to two weeks in duration. The tests were spread over an eight-month period and were interspersed with other tests designed to isolate the impact of daylight-linked lighting load reductions. Prior to each test, bulletins were distributed to occupants informing them in general terms of the nature of the test and reminding them to use the telephone overrides if necessary.

Monitoring instrumentation

Energy use for lighting was measured using the output record of the installed energy management system. Every time the lighting system changed state, either by a preprogrammed schedule or by a manual override, the system recorded which sector (or sectors) were changed and to what level. From this information, the electrical power to all the lighting on the floor or any subset of lights could be calculated. To facilitate processing and reduction of the experimental data, all lighting activities were recorded onto a magnetic data cartridge system as well as onto a hardcopy printer. Following each test event, the magnetic tape cartridges were shipped to LBL and the data transferred to the LBL 7600 and VAX 11/780 computers for analysis. A computer program was developed by one of the authors (Karayel) to translate the record of sector switching activity to a running record of lighting power demand.

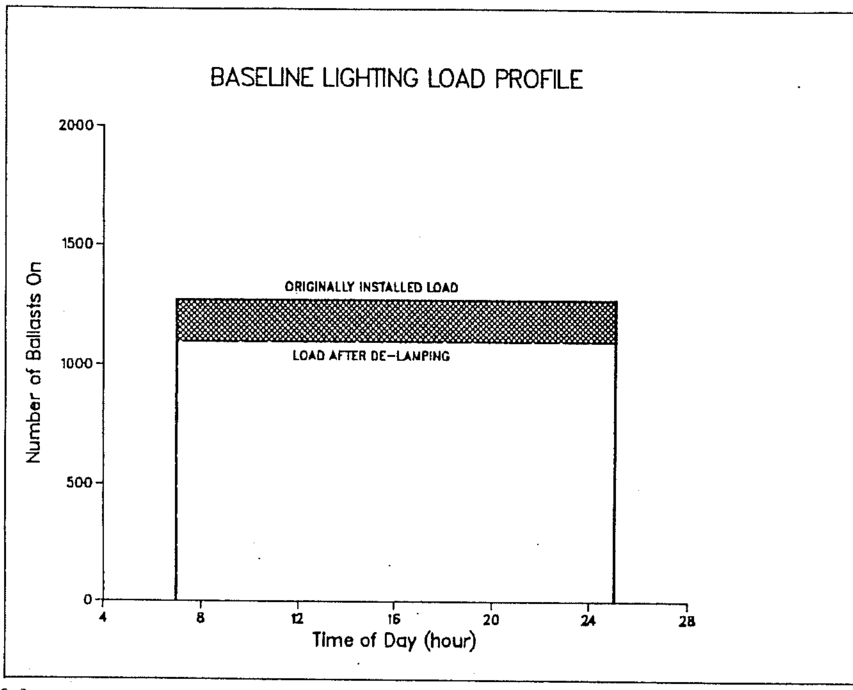
During the analysis of the experimental data, it was found that the sector for the conference room lights was being switched on and off at unpredictable times, making meaningful comparisons between similar test results difficult. As a result, we eliminated the switching activity of the conference room from our data in the reduction process.

Results

The results for each experimental event relating to the use of occupancy scheduling are shown as plots of number of ballasts (relays) turned on versus time of day for each day of the test. As each ballast was known to use 85-W, the number of ballasts on is directly proportional to the instantaneous lighting load. In our analysis, we have treated only weekday data because this floor of the World Trade Center is rarely used during the weekend and the results are therefore not meaningful.

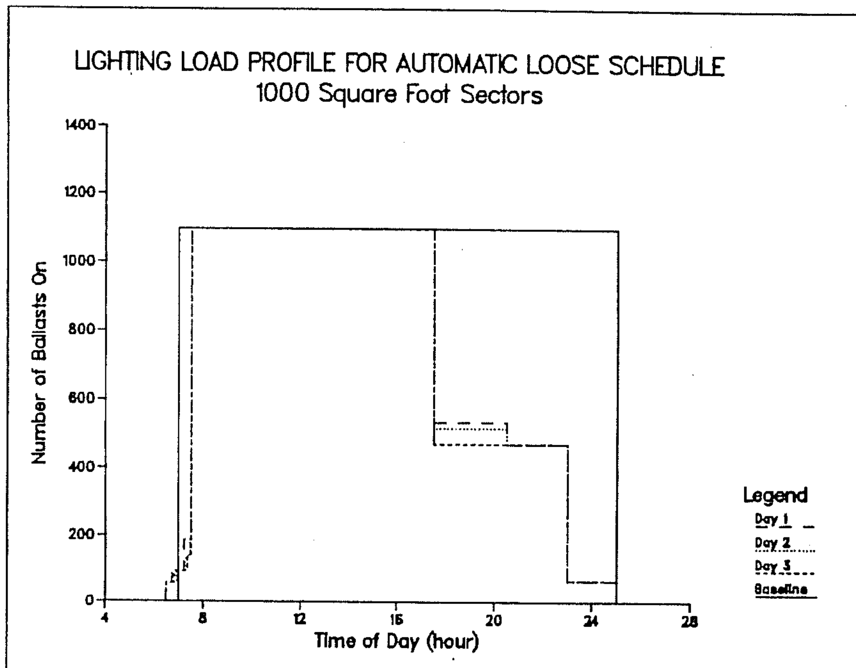
Baseline before and after delamping

[1] shows the lighting load profile for both the original lighting system and after delamping and relamping with 35-W lamps. The lighting demand for the original lighting system was 122 kW (1271 ballasts × 96-W/ballast) with average daily usage of 2196 kWh for the entire floor (excluding the conference room). Post-embargo lighting demand was reduced to 93 kW, (1096 ballasts × 85-W/ballast) with daily energy usage of 1677 kWh. Of this total reduction in demand (29 kW), 17 kW is attributable to the removal of 40 lamps over areas requiring less illumination. The remaining 12 kW reduction was due to replacing the remaining 40-W fluorescent lamps with 35-W lamps. For our analysis of the energy savings associated with scheduled lighting operation, we used the lower power profile as the baseline because this was the lighting power profile in effect immediately prior to this study.



[1]

[2]



Automatic loose schedule with 1000-ft² sectors

[2] shows the lighting power profile for each weekday for the test in which the lights were automatically switched on at 7:30 am and switched to one-third level for the evening cleaning tasks. The lighting usage attributable to occupants arriving before the automatically scheduled on-time at 7:30 am is evident in the figure. Between 5:30 pm and 8:30 pm, the measured lighting demand is somewhat higher than the programmed one-third level due to occupants using the overrides after 5:30 pm. Note that the lighting demand drops to approximately one-third of full level at 8:30 pm because the control system was programmed to switch all overridden sectors to one-third at this time. This technique of switching overridden sectors to low level at a pre-programmed time was adopted to prevent the lights in manually overridden sectors from remaining at full level throughout the evening. It is also evident from the figure that the lighting power profiles for different test days are quite similar despite the slight differences in override use patterns.

Using the automatically-activated loose schedule, lighting energy use was reduced from 1677 kWh/weekday to an average of 1178 kWh/weekday, a 30 percent reduction in daily lighting energy consumption.

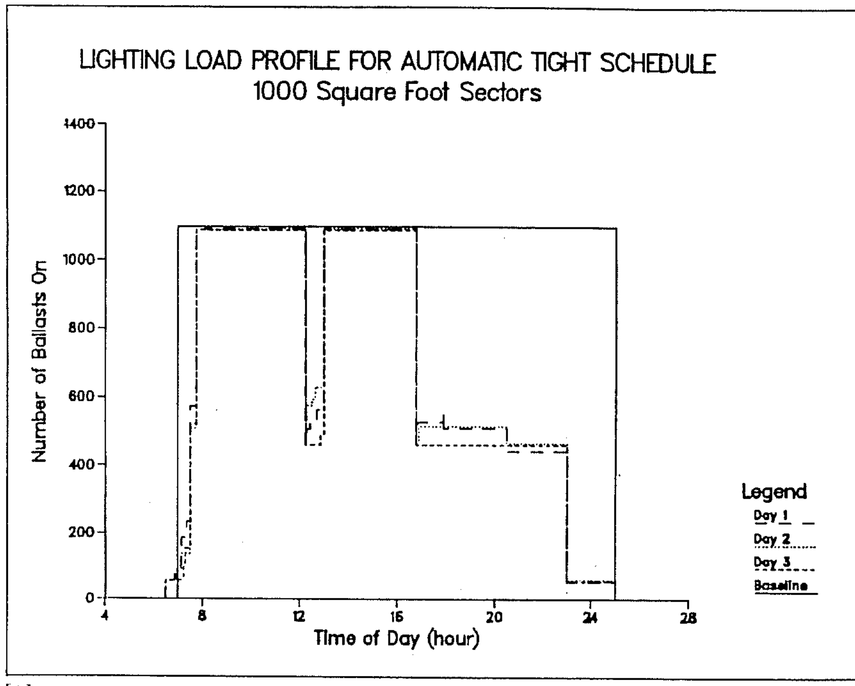
Automatic tight schedule with 1000–ft² sectors

[3] shows the lighting demand measured for weekdays during the second scheduling test. Full lighting was activated 15 minutes later (7:45 am) than in the previous test and light levels reduced to one-third level at 4:45 pm. Lighting demand between 12:15 pm and 1:00 pm was significantly reduced due to the automatically programmed lunch-time set-back. The lighting demand does not drop all the way to one-third, however, due to the use of overrides by individuals working through lunch time. Average lighting energy consumption for this test was 1077 kWh/weekday: a reduction of 36 percent relative to the baseline operation (delamped) and a 9 percent reduction relative to the automatic loose schedule described previously.

Manual on/automatic off schedule with 1000-ft² sectors

Further slight reductions in lighting power and energy use occurred when the first arrivals in each sector manually engage the lighting rather than having it provided automatically at a preprogrammed time. Lighting was automatically reduced to one-third level at 12:15 pm and at 4:45 pm as in the previous test. Because lighting in each 1000-ft² sector was not activated until the first individual to arrive switched the sector lights on, lighting demand in the early morning and afternoon was generally lower in these tests [4] than in either of the fully automatic schedule tests described previously. Note that lighting demand did not reach baseline levels until approximately 9:30 am. Following the lunch time set-back, lighting demand consistently fell short of the baseline level.

For these manual on/automatic off test days, lighting energy use averaged 1052 kWh/weekday, a reduction of 37 percent relative to the baseline case



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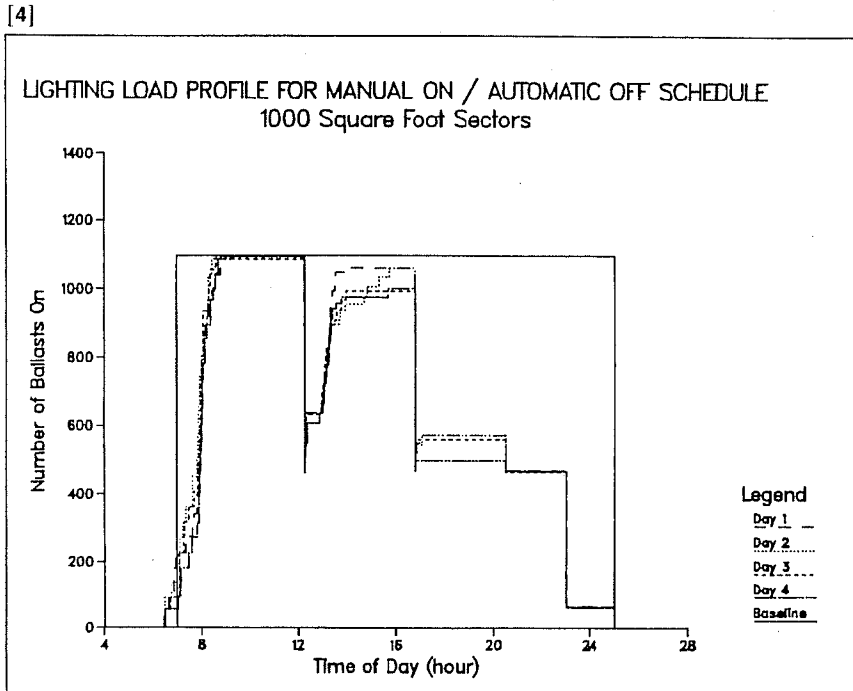
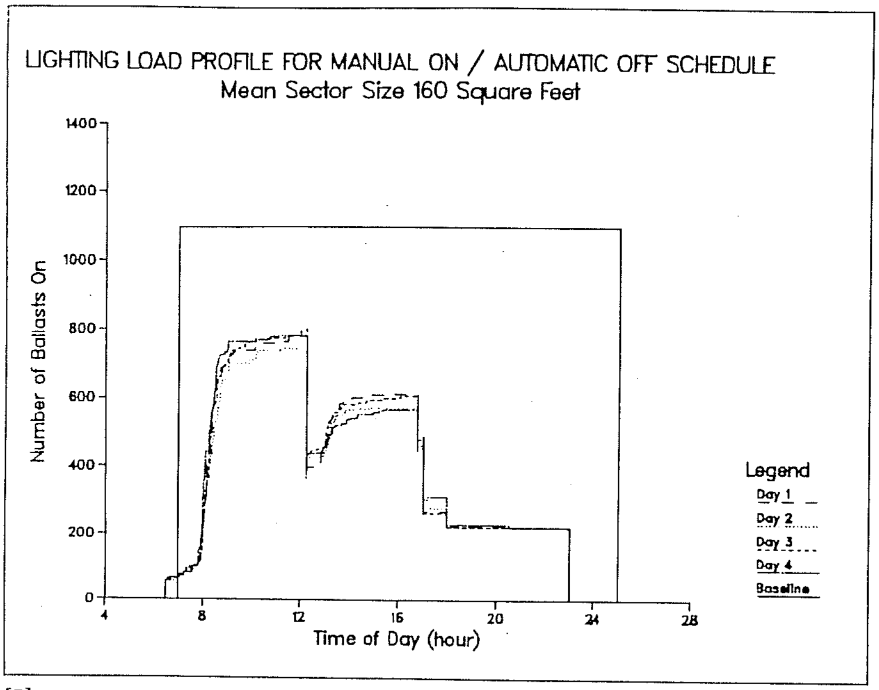


and an 11 percent reduction relative to the automatic loose scheduling test described earlier. Relative to the automatic tight schedule, manual on/automatic off control reduced average daily energy use by only 2 percent which is of questionable statistical significance.

Manual on/automatic off schedule with very small sectors

[5] shows the lighting power profiles for the manual on/automatic off schedule using workstation-sized sectors. It is evident from the graph that the utilization of very small sectors drastically reduced lighting demand throughout the day, especially in the afternoons. The automatic provision of stumble lighting is seen at 6:30 am for each day. Between 6:30 am and 8:00 am, there is a gradual increase in lighting demand as individuals arriving turned on the lights in their individual work areas. Since the vast majority of occupants arrive between 8:00 and 8:30 am, there is a rapid increase in demand during this time as these occupants engage their lights. Although the major influx of people entering the building space ends at 8:30 am, people still continue to arrive until about 11:00 am. The maximum lighting demand in the morning never exceeded 73 percent of the baseline lighting load. Following the lunch time set-back at 12:15 pm, a number of individuals immediately restored their lights to full level, presumably because they intended to work through lunch. Between 1:00 pm and 1:30 pm there is a rapid increase in lighting demand as expected; however, maximum lighting demand in the afternoon never exceeded 56 percent of the baseline demand. At 5:00 pm the lighting system is forced to the one-sixth level, and the few individuals working after this overrode their lights. All lighting was shut off at 11:00 p m. As the sectors in this experiment were very small (mean size 160 ft^2), any overrides after the evening reduction at 5:00 pm have only minor impact on the lighting demand.

Average lighting energy use for this test was only 604 kWh/weekday, a reduction of 64 percent relative to the baseline case and a 49 percent reduction beyond the automatic loose schedule test with 1000-ft^2 sectors.



[5]

Table 1

Reduction in Daily Lighting Energy Use and Percent Change from ↓

Relative To ↓	Manual On/ Automatic Off (Workstation Control)	Manual On/ Automatic Off	Tight Schedule	Loose Schedule
		(1000-ft² Sectors)		
Baseline	1073 kWh 64%	625 kWh 37%	600 kWh 36%	499 kWh 30%
Loose schedule w/1000-ft² sectors	574 kWh 49%	126 kWh 11%	101 kWh 9%	—
Tight schedule w/1000-ft² sectors	473 kWh 44%	25 kWh 2%	—	—
Manual on/automatic off schedule w/1000-ft² sectors	448 kWh 43%	—	—	—

Result summary

Table 1 summarizes the results of all the tests. The table is presented in matrix form to permit comparisons of the energy savings between the various tests.

To find the relative decrease in lighting energy use of, for example, the tight schedule relative to the loose schedule, one would select the row labeled loose and the column labeled tight to find that the daily lighting energy use reduction was 101 kWh, a decrease of 9 percent.

DISCUSSION

It is evident from the data presented here that scheduling the operation of the lighting system to conform more closely to occupancy needs and flow patterns can conserve a considerable amount of energy. In this building, as in many commercial buildings, the vast majority of occupants are present only during the core time, that is, between 8:00 am and 5:00 pm. With the exception of a few early arriving and late departing individuals, the only function of the lighting system outside the core hours is to provide light for the cleaning crew, whose tasks are not visually demanding. The 30 percent reduction in lighting energy use measured using the automatic loose schedule was almost entirely attributable to reducing light levels to one-third during non-core times.

By using the tight schedule, to switch the lights on slightly later in the morning and slightly earlier in the evening, we were able to reduce energy use an additional 9 percent relative to the loose schedule. Part of this savings was a consequence of the lunch time set-back, which significantly impacted lighting demand during the lunch hour. The placement of the set-back time at 12:15 pm rather than at noon is important because a premature level shift would probably cause the occupants to restore their sectors to full lighting even if they intended to depart momentarily for lunch. For similar reasons, we did not attempt a level reduction earlier than 4:45 pm with this test.

By allowing occupants to switch on their lights in the morning and after lunch, a further reduction in energy use was measured. Although the lighting load takes longer to reach the baseline level using the manual on/automatic off schedule than in previous tests, all sectors are eventually activated in the morning because several occupants share each 1000-ft² sectors, and therefore the probability is high that at least one individual will arrive and switch on the lights. It is interesting to note, however, that after the automatic lunch time set-back, a few sectors are consistently left at one-third level and were not restored to full lighting level by the occupants returning from lunch. One explanation for this behavior is that the one-third electric light level plus the availability of daylight was sufficient to obviate the need for full lighting during the afternoon. An alternative explanation is that some sectors are simply not occupied after the lunch hour due to occupants being offsite.

A comparison of the data from the tight and manual on/automatic off tests revealed only an insignificant difference in overall lighting energy consumption. This indicates that with 1000-ft² sectors there is little energy-saving benefit to be gained by having the workers turn on their own lights rather than providing light automatically at a preprogrammed time. There was some indication that manual on/automatic off control can reduce lighting demand during the afternoon hours, however.

The workstation control data showed a large reduction not only in overall energy use but also in lighting demand throughout the core hours. This result was in sharp contrast to the previous tests using 1000 ft^2 sectors in which lighting demand during the core hours was at best only slightly reduced. The cause of the lighting demand reduction with workstation control is due to several factors. First, the employment of extremely fine control resolution in this test permitted the elimination of about 100 ballasts located over under-utilized areas. Second, although lighting sectors were defined for all workstations, detailed analysis of the data revealed that 20 percent of the workstation sectors were never turned on during the entire test, presumably due to under-utilization of these areas. Third, even in those workstations that were usually occupied, absenteeism and vacancies accounted for some of the lighting load reduction. Finally, the even larger reductions in lighting load in the afternoon hours suggests that the availability of daylight in conjunction with the one-third electric lighting level may have been sufficient for some occupants' needs. The latter interpretation of the data is consistent with that of Crisp,[3] who found that the probability of occupants turning on their area lights after lunch was lower than 50 percent given daylight factors as low as 0.5 percent (typically 5 fc). Regardless of the interpretation, however, it is evident that the combination of very small sectors with manual on/automatic off control allows a considerable reduction in lighting demand throughout the core hours. Of course, the potential benefits of these reductions must be weighed against the formidable cost of providing this degree of control.

Use of overrides

The importance of overrides was demonstrated repeatedly throughout this study. If the probability distribution of people arriving and departing as a function of time was sharply peaked at known times and had no "tail," then overrides would not prove necessary because the lights could simply be switched on immediately prior to occupancy and switched off immediately after vacancy. This is rarely the case, however, since at least a few individuals will usually work outside regular core times. If overrides were not provided, it would be necessary to use a long lighting schedule to accommodate these individuals, significantly reducing any possible energy savings. By providing accessible override switches for local lighting sectors, a relatively tight schedule can be employed to provide lighting for the majority of people while the overrides are used to meet the lighting needs of those individuals who work outside the schedule on-times.

For the manual on/automatic off lighting schedules, overrides also served another useful function. Because the overrides must be used by the occupants to obtain light in their local areas, it is possible to capture some additional energy savings as a result of zone vacancies due to absenteeism, under-utilization of building space, and the availability of daylight. As our data indicate, the amount of energy that can be conserved under these conditions is directly related to the size of the switched sectors. On the other hand, the cost of the installed controls for this type of system increases in proportion to the number of independently-controllable sectors. This implies that there is an optimum sector size that can be determined for a particular energy cost and lighting power density if the occupancy distribution is known. More work needs to be done in this area, however, before it is possible to develop any generalized lighting control design procedures.

Economic analysis for 1000-ft^2 sector control

Based on the energy savings measured in this study, one can estimate the cost-effectiveness of automatic controls for scheduling for a large new construction project in which the lighting system is split-wired for multi-level control and controls are installed as part of the design process. Projecting the energy savings previously described to 260 working day per year, the loose scheduling technique would reduce annual lighting costs by $7,850 per floor relative to basecase costs assuming an energy cost of $0.06/kWh. Since the installed cost of the controls (relays, wiring, etc.) in a new construction situation is approximately $100 per control point (relay), the initial investment for the controls would be $5000/floor (25 sectors/floor × 2 relays/sector × $100/relay). From this one can calculate that the simple payback period (initial investment costs ÷ annual energy cost savings) for the loose scheduling technique is less than 8 months. Similarly, for the tight and manual on/automatic off schedules, the annual energy cost savings would be $9,420 and $9,680, respectively, yielding paybacks of between 6 and 7 months.

The brevity of the simple paybacks estimated above is of course due partly to the long baseline lighting schedule in effect prior to this study. To show that these scheduling techniques are still economical in buildings with shorter baseline hours, we recalculated the energy savings assuming a building in which the original lighting hours are 7:00 am to 9:00 pm. Because the baseline lighting hours are, in this case, only 14 hours a day instead of 18 hours, the energy savings for the loose, tight, and manual on/automatic off schedules relative to the modified baseline are reduced to 16 percent, 24 percent and 26 percent, respectively. Despite these reduced energy savings, annual energy cost savings are projected to be $3,260, $4,880, and $5,290 per floor with associated simple payback periods of 18, 12, and 11 months for the loose, tight, and manual on/automatic off schedules, respectively. Since paybacks of less than two years are generally considered acceptable for this kind of investment in new construction,[5] it is clear that the investment in control hardware to automatically schedule the operation of the lighting system can be economically justified.

Economic analysis for workstation control

Although the measured energy savings with the workstation-sized sectors was very large (64 percent relative to the baseline at World Trade Center and 57 percent relative to a building using the modified 14-hour baseline), this degree of control can only be economically justified if energy costs are very high. Workstation control requires the installation of two relays per fixture; the cost of installation would therefore be about $90,000/floor in a new construction situation. At $0.06/kWh, the projected energy cost savings are $16,740/floor/year relative to the World Trade Center's 18-hour baseline and $11,600/floor/year relative to the 14-hour baseline. Since this equates to payback periods of 5.4 and 7.8 years respectively, installation of this degree of control is not economical. At $0.14/kWh (current electrical energy costs in New York City), the paybacks would be 2.3 and 3.3 years.

Interaction with heating and cooling loads

In our analysis, we have not considered the impact of reduced lighting energy consumption on heating and cooling loads. It is clear that one consequence of automatically scheduled lighting is decreased cooling loads and increased heating loads. Although there are undoubtedly some buildings in cold climates where the increase in heating loads would reduce the net savings from scheduled lighting, it is also true that in most large buildings cooling loads dominate. In the latter cases, any reduction in lighting energy consumption only adds to energy savings due to the accompanying reduction in cooling loads.

Conclusion

It is evident from this study that automatically scheduling the operation of the lighting system to closely conform to occupancy patterns substantially reduced energy consumption for lighting. Using a simple loose schedule technique with 1000-ft^2 sectors, a 30 percent reduction in lighting energy use was measured relative to baseline operation. By employing a tighter automatic schedule, lighting energy use was reduced 36 percent relative to baseline operation with similar results for a manual on/automatic off switching technique. With work station-sized sectors, lighting energy use was reduced 64 percent relative to baseline operation, clearly demonstrating the relationship between energy savings and sector size. Using a simple economic analysis, we have shown that automatic scheduling with 1000-ft^2 sectors is a cost-effective method to reduce lighting energy consumption in buildings.

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